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Quarterly Progress Report
Advanced Nuclear Electric Power Generator System Study (U)
Report PWA-2157 Volume III
Rankine Cycle Nuclear Space Powerplant

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Pratt & Whitney Aircraft DIVISION OF UNITED AIRCRAFT CORPORATION

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I. INTRODUCTION

Pratt & Whitney Aircraft Division is conducting a study of nuclear-electric space powerplants in the one megawatt size range under contract to the National Aeronatuics and Space Administration. Two types of powerplants are being investigated. This volume describes the work accomplished on a high temperature Rankine cycle nuclear space power system during the period October 1 through December 31, 1962. The results of other related studies by Pratt & Whitney Aircraft are also included.

The scope of work being performed in this study includes parametric analysis of powerplants in the range of one megawatt electric power. Component parametric data has been developed and has been incorporated in a system optimization study. Component designs are being developed and these components will be integrated into a system design which is intended to meet the limits of the Saturn C1B launch vehicle. Topical reports will be issued covering the parametric studies and the reference design.

The objectives of this study are:

1) to investigate characteristics unique to the system,
2) to identify the technical uncertainties unique to the system, including design, material and fabrication considerations, and
3) to recommend future program areas for the study of feasibility and state-of-the-art limitations.

II. SUMMARY

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A table of thermodynamic design requirements has been developed on the basis of preliminary system optimization. The table is based on a reactor outlet temperature of 2000°F and a turbine inlet temperature of 1850°F. A once-through boiler with nominal superheat has been selected for the reference design. The turbine is an 8-stage machine with provisions for interstage separation of moisture. Auxiliary cooling is provided by an independent potassium loop. Parametric data developed by the Westinghouse Electric Company under contract NAS5-1234 was used in the selection of the electrical system characteristics and generator speeds. Turbine blade stress limit curves have been developed. Design studies have been initiated on turbine generator-pump unit, condenser, and radiator. A preliminary general arrangement is being prepared

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Author

III. DESCRIPTION OF RANKINE CYCLE POWERPLANT

The Rankine cycle powerplant is composed of four major subsystems. In the primary system, two canned rotor pumps circulate liquid lithium which cools a reflector-controlled reactor and transfers heat to the power conversion system through four potassium boilers. Each boiler delivers potassium vapor to a power conversion system turbine which is directly connected to a generator, a condensate pump, and an auxiliary coolant pump. The exhaust from each turbine is condensed in four potassium condensers. Each condenser is cooled by an independent lithium loop which rejects heat in one of sixteen main radiator segments. The auxiliary coolant pump in each power conversion system circulates potassium through the various auxiliary heating loads and an auxiliary radiator. Figure 1 is a simplified flow diagram showing key cycle conditions.

A. Primary System

The power source is a compact, lithium-cooled reactor, fueled with uranium monocarbide. The reactor core is in a pressure vessel in which lithium enters at 1900°F and is heated to 2000°F. The reflector surrounding the reactor vessel is cooled by direct radiation to space. Reactor control is achieved by varying neutron leakage through movement of the reflector.

The lithium is circulated through the primary system by electric motor-driven pumps of the canned rotor type. The motor is cooled by lithium circulating through a heat exchanger which is cooled by potassium from the auxiliary coolant system. Hydrodynamic bearings cooled with lithium at a reduced temperature are used.

Reactor shielding is provided to reduce radiation in the vicinity of the payload to a level acceptable for operation of semiconductors for the life of the powerplant. The heat from the primary circuit is used to generate potassium vapor at 1850°F with nominal superheat for control purposes.

B. Power Conversion System

The potassium vapor turbine (Figure 2) is a full admission 8-stage unit incorporating interstage separation of moisture. The turbine

RANKINE CYCLE SPACE POWERPLANT

SCHEMATIC DIAGRAM

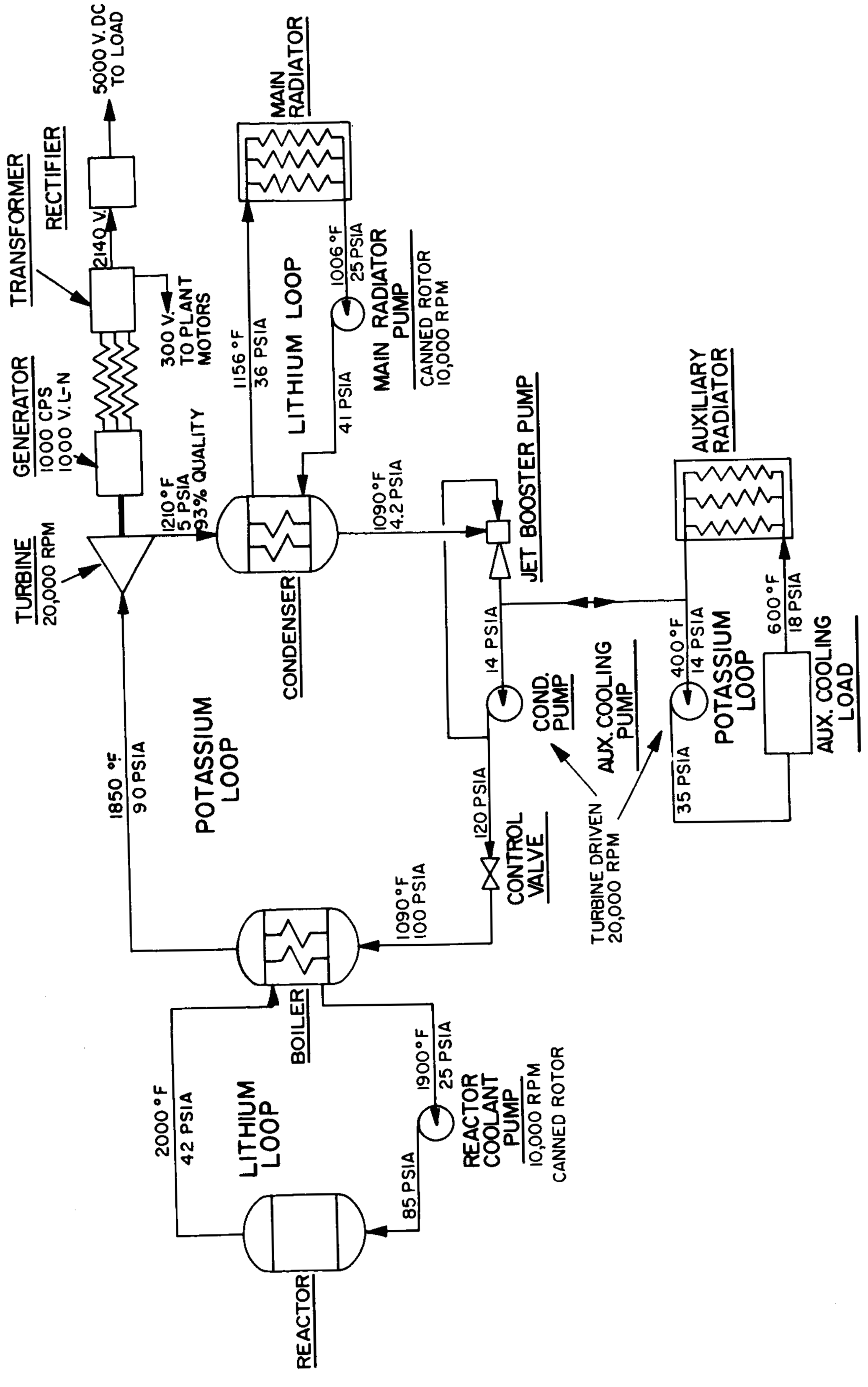

Figure 1

TURBINE GENERATOR

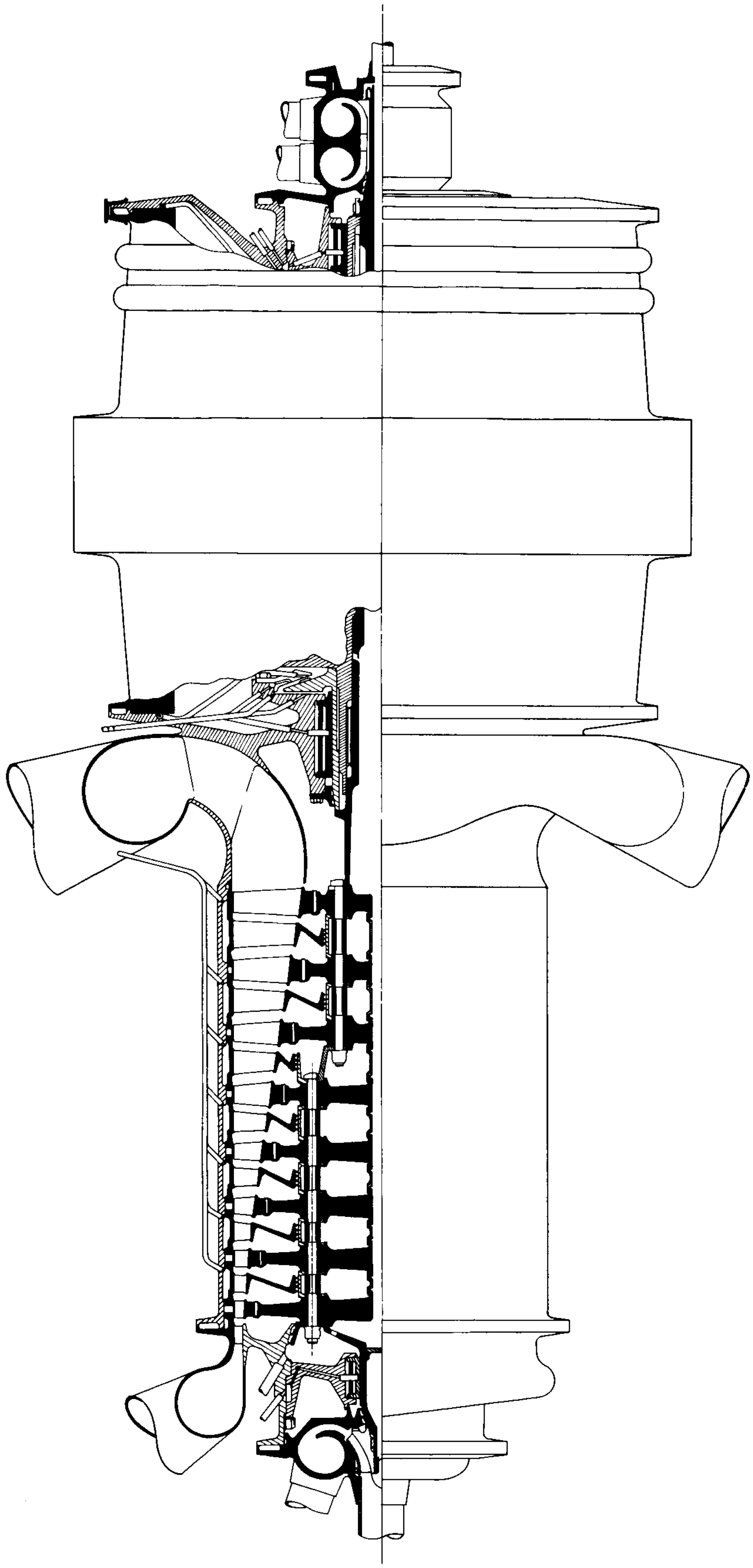

Figure 2

is directly connected to a generator, condensate pump, and auxiliary cooling pump. Hydrostatic and hydrodynamic bearings are being evaluated for use in this unit. Seals are provided to prevent liquid potassium from entering the generator gap during operation, and a positive means of pumping is provided to maintain the pressure in the gap well below the saturation value so that condensation is eliminated. The generator rotor is cooled by branch flow from the auxiliary coolant pump.

The condensate pump is a centrifugal unit driven from the high pressure end of the turbine. The pump supplies all boiler flow requirements and motive power for jet booster pumps which raise the suction pressure of the condensate pump so that its suction specific speed is low enough to be consistent with the long life and high reliability required for the powerplant.

The exhaust from each turbine is condensed in the tubes of four shell and tube heat exchangers (Figure 3) with coolant circulated counterflow on the shell side.

C. Main Heat Rejection System

Each condenser is cooled by lithium which is circulated through the condenser and one main radiator segment by a canned rotor centrifugal pump. Each segment consists of tapered inlet and outlet headers connected by a series of small diameter tubes with beryllium fins. The radiator will be deployed in a plan form configuration after orbit is established. Meteoroid protection is provided by a beryllium barrier.

D. Auxiliary Cooling System

The main generators, transformer and all liquid metal pump motors are cooled by potassium which is pumped by an auxiliary circulating pump connected to the turbine-generator shaft at the generator end. The auxiliary coolant pump also supplies low temperature potassium to the turbine generator bearings. The auxiliary heat loads are rejected in a radiator panel similar in construction to the main radiator panels.

Cooling of electronic equipment incorporating semiconductors will be accomplished by a low temperature cooling system in which the

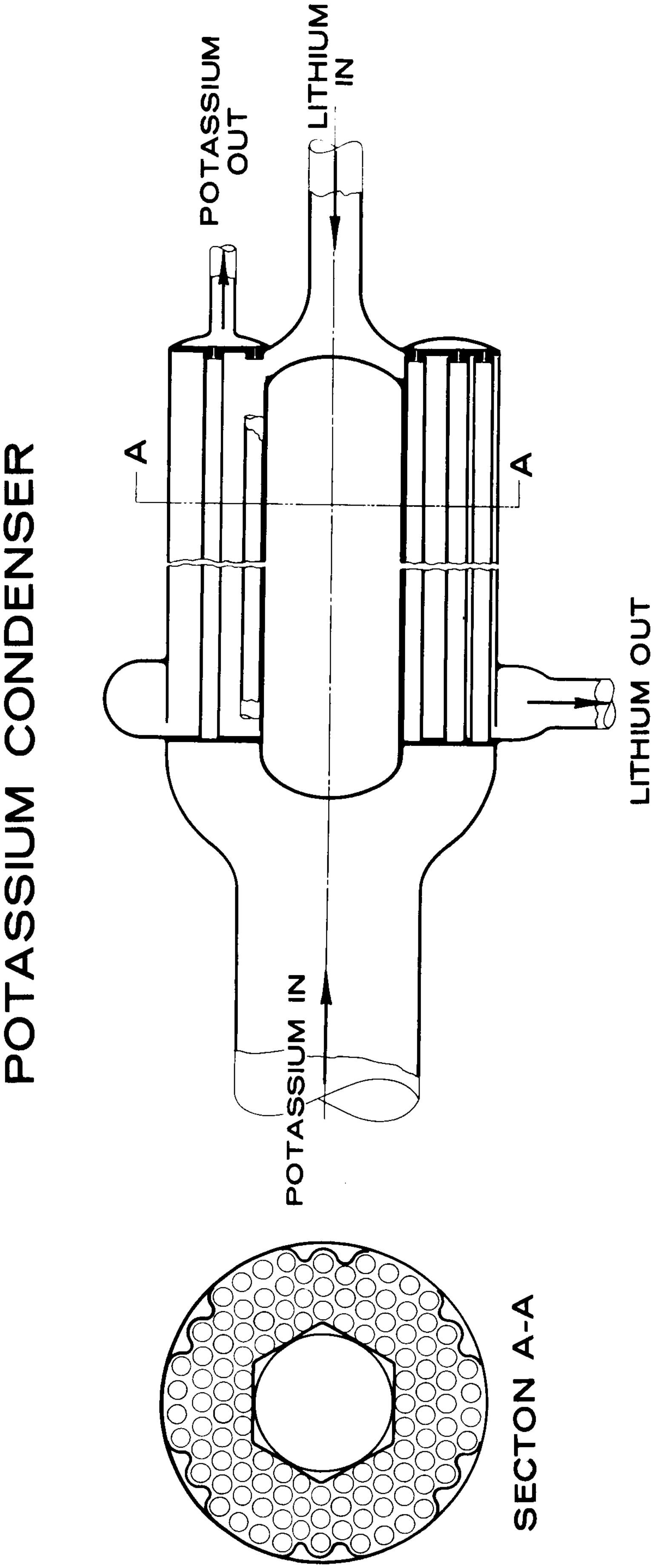
POTASSIUM CONDENSER
POTASSIUM OUT
LITHIUM IN
A
A
LITHIUM OUT
POTASSIUM IN
SECTON A-A

Figure 3

coolant will be methylisopropylbiphenyl as specified by Westinghouse in work reported in Reference 1. The units served by this system are: the main rectifier which converts 3-phase 1000-cycle power at 2140 volts (line-to-neutral) to 5000 volts DC at the output bus, the exciter regulator which controls generator voltage, and control and instrumentation electronics.

E. Arrangement

A preliminary general arrangement (Figure 4) illustrates how the powerplant can be installed within the envelope of the Saturn C1B payload. Half of the radiator segments are shown deployed in the operating configuration and, the other half stowed in the launching configuration.

POWERPLANT ARRANGEMENT

1 MW RANKINE CYCLE POWERPLANT STUDY

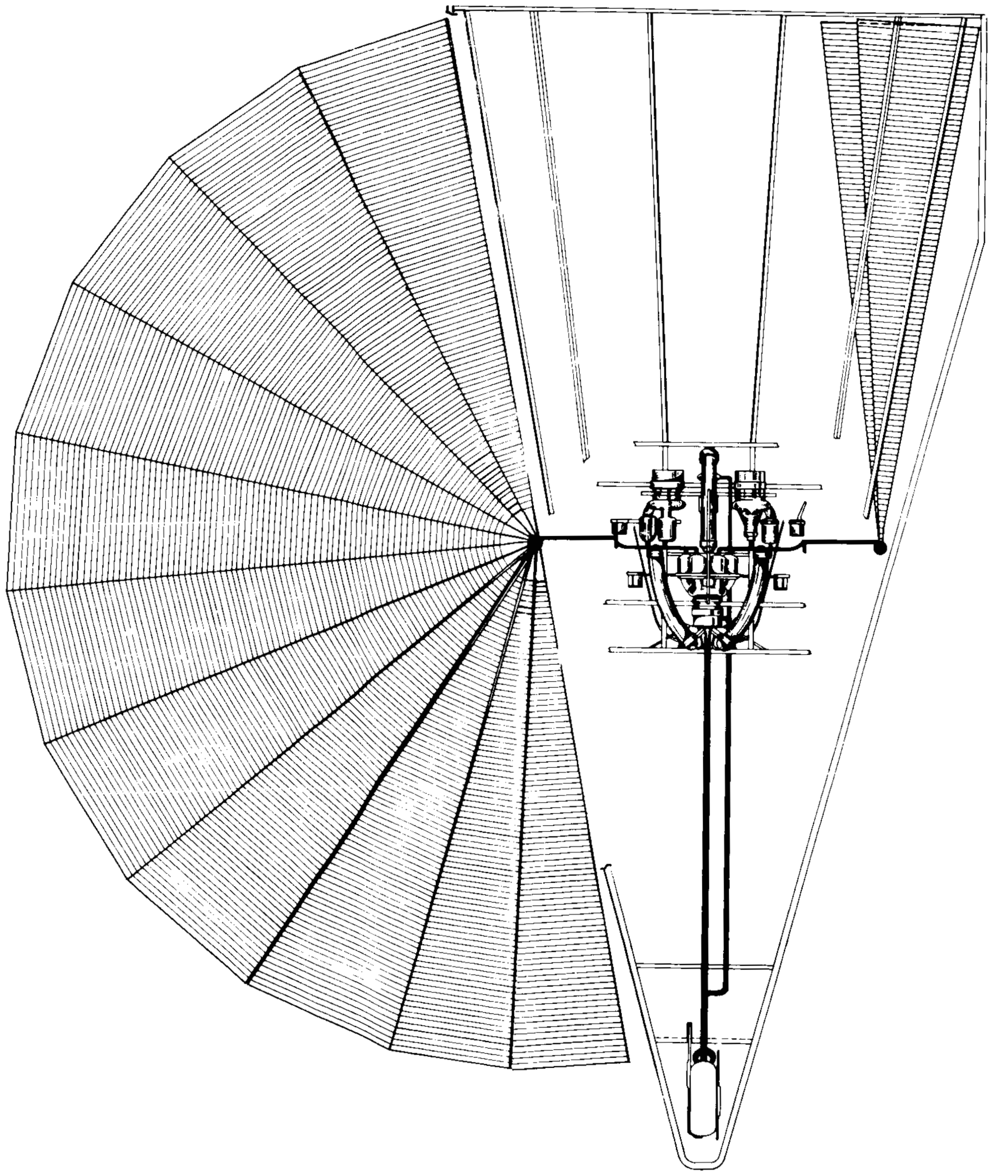

Figure 4

IV. DISCUSSION OF WORK PERFORMED

A. System Design

The component parametric work reported in the first quarterly progress report (Reference 2) has been used to establish power-plant design conditions for a system with a net output of one megawatt electric. Table 1 is a summary of the design requirements at rated power. Detailed quantities are presented for the power conversion system which supplies the maximum auxiliary power load. The breakdown of auxiliary loads for each loop and the associated boiler power is:

	Loop 1	Loop 2	Loop 3	Loop 4
Primary coolant pump	1	1	-	
Main radiator pump	4	4	4	4
Low temperature radiator pump	1	1	-	-
Reactor and control instrumentation	1	-	-	-
Boiler power, KW	1530	1516	1375	1375

The reactor power is 5796 KW, which is the sum of the boiler power in each loop. The generator power listed in Table 1, 294.5 KW, is that required to deliver 250 KW of DC power with only one of four power conversion systems operable. The auxiliary power required under these conditions is 33 KW at the 300-volt terminals of the power transformer. The design requirement established for the transformer is 50 KW at the 300-volt terminal. A margin of 17 KW is not excessive at this stage of design. The design requirement for the generators is 325 KW including a 15 KW margin for parasitic load in the event that such a load is required for control.

B. Component Design and Arrangement

Turbine-Generator

Figure 2 is an elevation of the turbine-generator pump unit. Provisions for the extraction of moisture between stages are shown. The concept is similar to saturated steam turbine practice in which bleedoff ports are provided in way of moisture which is thrown off the rotor blade tips. Each bleedoff port is vented to the exhaust scroll through orificed bleed lines. Interstage moisture extraction is important because it results in a significant improvement in turbine efficiency and reduces the moisture in any stage to a maxi-

TABLE 1
Design Requirements
1MW Rankine Cycle Space Powerplant

A. Primary System

1. Reactor (1 required)	
Flow, lb/sec	58.8
Power, KW	5796
Inlet Temp., °F	1900
Inlet enthalpy, BTU/lb	2272.3
Inlet pressure, psia	85
Exit temp., °F	2000.
Exit enthalpy, BTU/lb	2371.
Exit pressure, psia	55
2. Boiler (4 required)	
Heat transferred, KW	1530
Potassium side	
Flow, lb/sec	1.526
Inlet temp., °F	1056.2
Inlet enthalpy, BTU/lb	286.2
Inlet pressure, psia	100.
Exit temp., °F	1850
Exit enthalpy, BTU/lb	1237.7
Exit pressure, psia	89.3
Exit quality, % Vap	100.
Exit superheat, °F	15.0
Lithium side	
Flow, lb/sec	14.7
Inlet temp., °F	2000.
Inlet enthalpy, BTU/lb	2371.0
Inlet pressure, psia	45
Exit temp., °F	2000
Exit enthalpy, BTU/lb	2272.3
Exit pressure, psia	30
3. Primary Coolant Pump (2 required)	
Type	Centrifugal
Speed, RPM	10000
Flow, lb/sec	29.4
Volumetric flow, gal/min	430
Shaft power, KW	17.8
Inlet temp, °F	1900
Inlet enthalpy, BTU/lb	2272.3
Inlet pressure, psia	30
Exit temp, °F	1900
Exit enthalpy, BTU/lb	2272.3
Exit pressure, psia	95
Head rise, ft	342

TABLE 1 (Cont'd)

B. Power Conversion System

1. Turbine (4 required)	
Number of stages	8
Speed, RPM	20000
Potassium flow, lb/sec	1.526
Shaft power, KW	315.4
Inlet temp., °F	1850.
Inlet enthalpy, BTU/lb	1237.7
Inlet pressure, psia	89.3
Inlet quality, % Vap	100.
Inlet superheat, °F	15.0
Exit temp., °F	1189.
Exit enthalpy, BTU/lb (in exhaust scroll)	1041.7
Exit pressure, psia	4.34
Exit quality, % Vap (in exhaust scroll)	83.9
Last stage quality, % vapor	92.8
2. Main Condenser (16 required)	
Heat load, KW	304
Potassium side	
Flow, lb/sec	.382
Inlet temp., °F	1175
Inlet enthalpy, BTU/lb	1041.7
Inlet pressure, psia	3.95
Exit temp., °F	1053.0
Exit enthalpy, BTU/lb	285.6
Exit pressure, psia	3.41
Exit subcooling, °F	100
Liquid lithium side	
Flow, lb/sec	1.9
Inlet temp., °F	1000.2
Inlet pressure, psia	39.9
Exit temp, °F	1150
Exit pressure, psia	39.2
3. Jet Pump (4 required)	
Inlet from feedback flow, lbs/sec	.762
Temp., °F	1056.2
Enthalpy, BTU/lb	286.2
Pressure, psia	120
Inlet from 4 condensers flow, lbs/sec	1.526
Inlet temp., °F	1053
Inlet enthalpy, BTU/lb	285.6
Inlet pressure, psia	3.41
Exit flow, lb/sec	2.288
Exit temp., °F	1054
Exit enthalpy, BTU/lb	285.9
Exit pressure, psia	14

TABLE 1 (Cont'd)

4. Potassium Pump (4 required)

Type	Centrifugal
Speed, RPM	20000
Flow, lb/sec	2.288
Volumetric flow, gal/min	23.2
Shaft power, KW	1.99
Inlet temp, °F	1054
Inlet enthalpy, BTU/lb	285.9
Inlet pressure, psia	14.
Exit temp., °F	1056.2
Exit enthalpy, BTU/lb	286.2
Exit pressure, psia	120.
Head rise, ft	343

5. Radiator Pump (16 required)

Type	Centrifugal
Speed, RPM	10000
Flow, lbs/sec	1.900
Volumetric flow, gal/min	29.3
Shaft power, KW	.67
Inlet temp, °F	1000
Inlet pressure, psia	15
Exit temp., °F	1000.2
Exit pressure, psia	36.2
Head rise, ft.	103

6. Main Radiator (16 required)

Heat rejected, KW	304
Flow, lb/sec	1.900
Inlet temp., °F	1150
Inlet pressure, psia	30.0
Exit temp., °F	1000
Exit pressure, psia	20

C. Auxiliary Cooling System

1. Auxiliary Radiator (4 required)

Heat rejected, KW		46
Coolant flow to generator, lb/sec	1.096	
Coolant flow to primary pump motor, lb/sec	.539	
Coolant flow to radiator pump motor, lb/sec	.171	
Coolant flow transformer, lb/sec	.287	
Coolant flow controls and other, lb/sec	.207	
Total flow, lb/sec		2.3
Inlet temp., °F		550
Inlet enthalpy, BTU/lb		193.1
Inlet pressure, psia		18.0
Exit temp., °F		450
Exit enthalpy, BTU/lb		175.0
Exit pressure, psia		14.0

TABLE 1 (Cont'd)

2. Auxiliary Radiator Pump (4 required)		
Type		Centrifugal
Speed, RPM		20000
Flow, lb/sec		2.3
Volumetric flow, gal/min		21.2
Shaft power, KW		.38
Inlet temp., °F		450
Inlet enthalpy, BTU/lb		175.0
Inlet pressure, psia		14.0
Exit temp., °F		450.5
Exit enthalpy, BTU/lb		175.0
Exit pressure, psia		34
Head rise, ft		59.7
3. Auxiliary Cooling System Heat Loads (for each loop)		
Heat load, KW		
Generator	21.9	
Primary pump motor	10.8	
Radiator pump motor	3.44	
Reflector, Shielding, Controls	4.06	
Transformer	5.8	
Total heat load, KW		46
Component coolant flow, lb/sec		2.3
Component coolant inlet temp., °F		450.5
Component coolant inlet enthalpy, BTU/lb		175.0
Component coolant inlet pressure, psia		34
Component coolant exit temp., °F		550
Component coolant exit enthalpy, BTU/lb		193.1
Component coolant exit pressure, psia		20.0
4. Rectifier Cooling System (2 required)		
Fluid Monoisopropyl Biphenyl		
Cooling Load, KW		6.0
Component coolant inlet temp., °F		165
Component coolant inlet pressure, psia		33
Component coolant exit temp., °F		175
Component coolant exit pressure, psia		31
Component coolant flow, lb/sec		1.33
Radiator		
Heat rejected, KW		6.0
Flow, lb/sec		1.33
Inlet temp., °F		175
Inlet pressure, psia		30
Exit temp., °F		165
Exit pressure, psia		26.0

TABLE 1 (Cont'd)

Pump		
Type		Centrifugal
Speed, RPM		10000
Flow, lb/sec		1.33
Volumetric flow, gal/min		10.6
Shaft power, KW		.11
Inlet temp., °F		165
Inlet pressure, psia		25.0
Exit temp., °F		165
Exit pressure, psia		34.0
Head rise, ft.		28.2

D. Electrical System

1. Generator (4 required)

Frequency, cps		1000
Speed, RPM		20000
Input power, KW		313.2
Output voltage, volts		1000
Output power, KW		294.5
Field power required, KW		3.2
Losses, KW		21.9

2. Transformer (4 required)

Frequency, cps		1000
Input voltage, volts		1000
Input power, KW		291.3
Output voltage, volts		
Winding #1		As specified by Westinghouse
Winding #2		300
Output power, KW		
Winding #1		252.5
Winding #2		33
Losses, KW		5.0

3. Transformer Hotel Load, KW

Primary pump motor	26.1	
Radiator pump motor	4.12	
Low Temp. radiator	.19	
Reactor drums, controls, other instruments	2.62	
Total	33.0	33.0

4. Rectifier (4 required)

Input voltage		As specified by Westinghouse
Input power, KW		252.5
Output voltage, volts		5000
Output power, KW		250.
Losses, KW		2.5

TABLE I (Cont'd)

5. Pump Motors	
a. Primary (2 required)	
Frequency, cps	1000
Number of poles	12
Speed, RPM	10000
Input voltage, volts	300
Input power, KW	26.1
Output power, KW	17.8
Losses, KW	8.3
b. Main Radiator (16 required)	
Frequency, cps	1000
Number of poles	12
Speed, RPM	10000
Input voltage, volts	300
Input power, KW	1.03
Output power, KW	.67
Losses, KW	.36
c. Low Temp. Radiator	
Frequency, cps	1000
Number of poles	12
Speed, RPM	10000
Input voltage, volts	300
Input power, KW	.19
Output power, KW	.11
Losses, KW	.08

mum of about 8 per cent. For an eight-stage turbine without moisture separation the last stage moisture would exceed 15 per cent.

Hydrodynamic and hydrostatic bearings are being evaluated. Disc cooling may be required for the first three or four stages. Additional parametric data relating to turbine stress limits is reported in Appendix 2.

Condenser

Mechanical design of the potassium vapor condenser was started (Figure 3). The tube bundle has been arranged in an annular configuration to improve the shell side flow distribution. The L/D is 3 to 1 for the annular tube bundle compared with 1 to 1 for a cylindrical tube bundle. The material of construction is Cb-1Zr.

Arrangements

Two radiator configurations have been considered. One is a skew axial arrangement with panels in four quadrants. The axes are arranged so that a single rotation of each panel will bring the entire radiator into a planar configuration. The other radiator concept is shown in the general arrangement drawing (Figure 4). This radiator incorporates several pie-shaped segments, each mounted at its apex on a common axis.

The radiator deploys like a fan. It stows in a minimum volume which offers considerable advantages for startup schemes which depend on filling the radiator before launching and insulating it until startup can be initiated.

Figure 4 is a preliminary general arrangement of the powerplant installed in the Saturn C-1-B payload envelope. The fan type radiator is shown stowed for launching and also deployed. The component sizes are approximate, but are accurate enough to give a good indication of how a one megawatt electric Rankine cycle powerplant will fit into the launch vehicle which has been selected. Ample room is available for the payload.

C. System Analysis

Optimization of Turbine Stages

Figure 5 summarizes the results of an investigation of the optimum number of turbine stages. The values shown are normalized to the case of a seven-stage turbine. As the number of turbine stages increases the turbine flow required decreases. This results in reduction in the weight of the boiler and primary system and condensate pump power. The significant quantity which is a measure of the size of the heat rejection system, (condensers, radiators and radiator pumps), is the ratio of heat rejected to condensing temperature (Q_{rej}/T_c^4). This ratio is the controlling parameter in the selection of the number of turbine stages. An 8-stage turbine has been selected as a reasonable compromise between radiator area and powerplant weight. In making this study, turbine inlet temperature was held constant at 1850°F. The amount of subcooling in the condenser was fixed at 100°F, and primary system weight was assumed proportional to boiler power at 3 lbs/KWe.

Auxiliary Cooling System Selection

Three approaches to the design of the auxiliary cooling system are shown in Figure 6. Using branch flow from the condensate pump requires the minimum equipment however there is a weight penalty in the excess heat which must be rejected to reduce the condensate used for auxiliary cooling from around 1100°F to 400°F. Some of this heat may be recovered by introducing a regenerative heat exchanger. However, there is little difference in the system weight with and without the regenerator.

A system which uses a separate auxiliary cooling circuit has been selected. A significant reduction in weight and boiler power is achieved because it is possible to meet theauxiliary cooling requirements without rejecting excess heat. A separate pump driven by the main turbine is used to circulate the auxiliary coolant. This provides a reliable prime mover and minimizes pumping power requirements. The suction of the condensate pump and auxiliary cooling pump is connected by a surge line to compensate for volume changes in the auxiliary cooling system, and to replace liquid lost through bearing leak-off to the condensate pump suction.

EFFECT OF NUMBER OF TURBINE STAGES

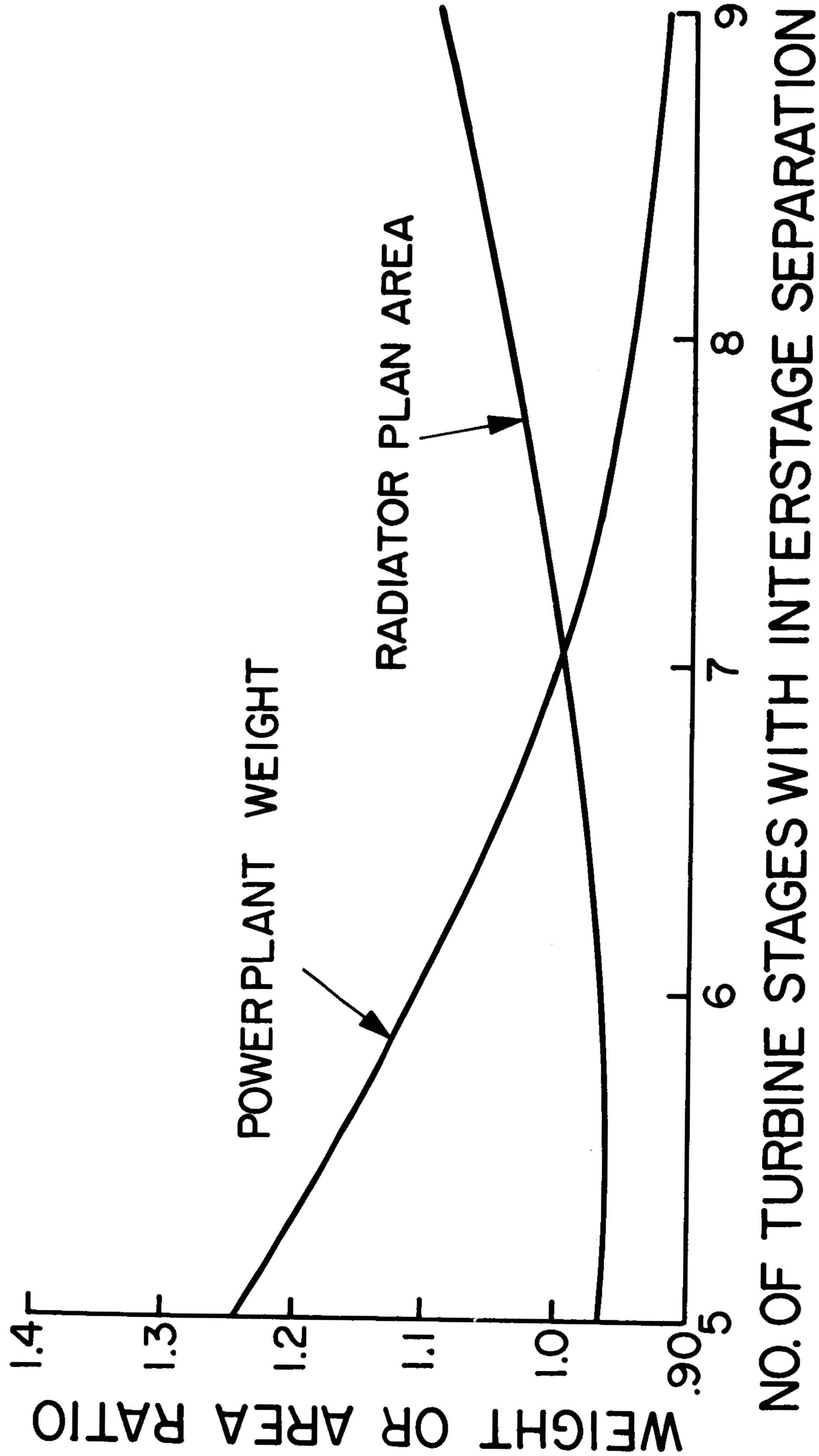

Figure 5

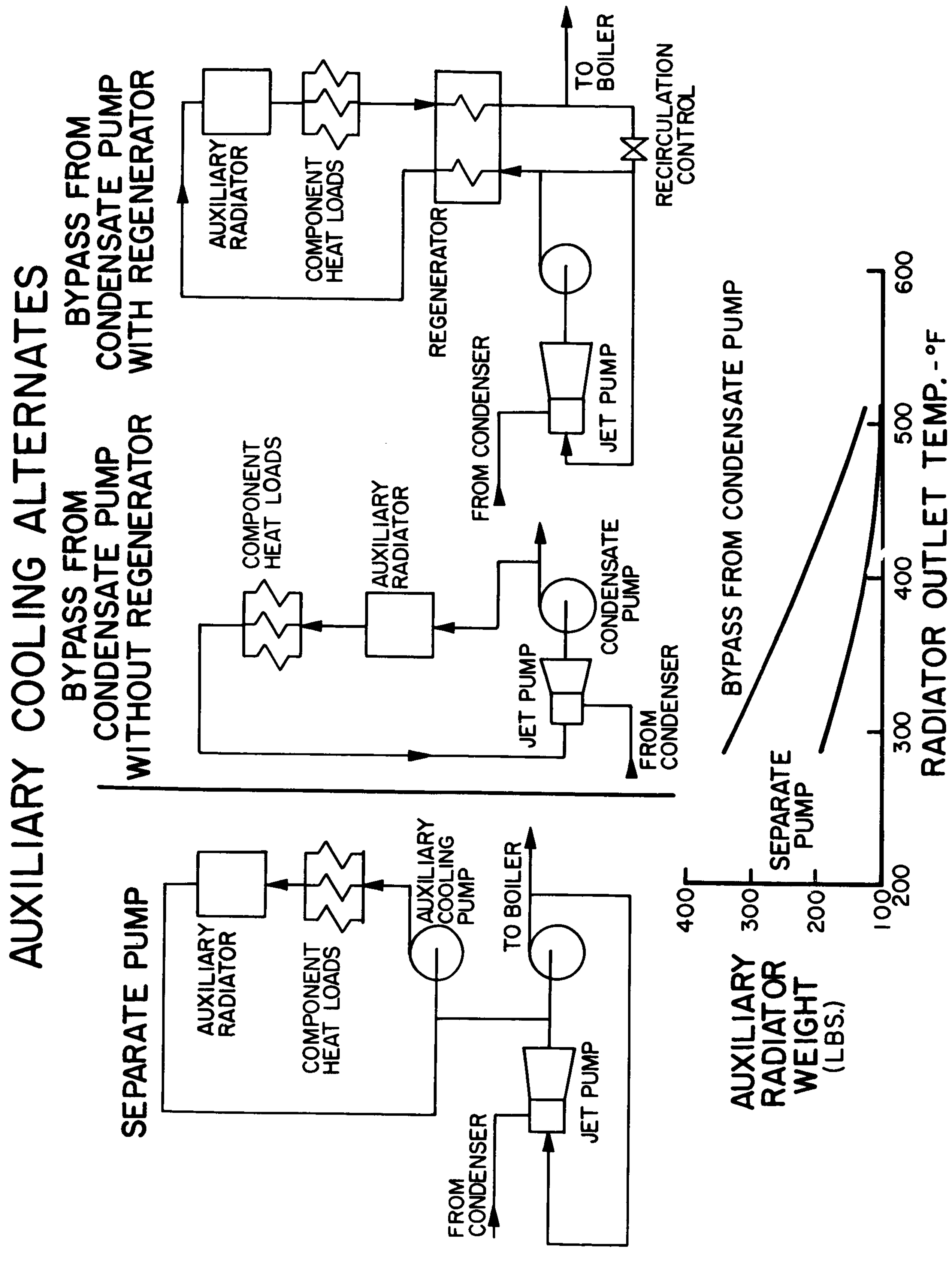
AUXILIARY COOLING ALTERNATES
SEPARATE PUMP
AUXILIARY RADIATOR
COMPONENT HEAT LOADS
AUXILIARY COOLING PUMP
TO BOILER
FROM CONDENSER
JET PUMP
BYPASS FROM CONDENSATE PUMP WITHOUT REGENERATOR
COMPONENT HEAT LOADS
AUXILIARY RADIATOR
CONDENSATE PUMP
JET PUMP
FROM CONDENSER
BYPASS FROM CONDENSATE PUMP WITH REGENERATOR
AUXILIARY RADIATOR
COMPONENT HEAT LOADS
REGENERATOR
TO BOILER
RECIRCULATION CONTROL
FROM CONDENSER
JET PUMP
AUXILIARY RADIATOR WEIGHT (LBS.)
400
300
200
100
200
300
400
500
600
RADIATOR OUTLET TEMP. - °F
SEPARATE PUMP
BYPASS FROM CONDENSATE PUMP

Figure 6

Boiler Concepts

A once-through boiler with nominal superheat for control purposes has been selected for the reference design. Another concept considered is a boiler with controlled circulation and external moisture separation. The two concepts are shown schematically in Figure 7. In the once-through system, potassium vapor is generated with a nominal amount of superheat, expanded in the turbine, condensed and returned to the boiler by the condensate pump. In the system incorporating recirculation, potassium is evaporated to a relatively low quality vapor. Moisture is extracted in an external separator and saturated vapor is supplied to the turbine. Turbine exhaust is condensed and returned to the boiler by the condensate pump and boiler circulating pump in series. The moisture extracted in the external separator is subcooled by the condensate in a regenerative subcooler and supplied to the suction of the boiler circulating pump with sufficient subcooling to prevent cavitation in this pump. The once-through system has been selected because it appears to offer a simpler method of control. It is likely that the once-through boiler system will be heavier than the recirculating system including separator, regenerative subcooler and circulating pump.

An extensive study of the control concept has not yet been made. Consideration should be given to a control system that does not require a control valve to operate at turbine inlet conditions. Without a control valve at the inlet turbine, flow control must be accomplished by adjusting the pressure drop across the turbine. With the once-through boiler, this can be accomplished by throttling the discharge of the condensate pump to match the turbine load. When the turbine load is reduced from full power, boiler pressure will be reduced, the potassium outlet temperature will increase slightly so that the amount of superheat will increase. Two significant factors are worth noting. The potassium inventory in the boiler will be reduced at part load, but the condenser will operate with a lower average coolant temperature so that the potassium inventory in the condensers will increase. This will minimize the surge volume required in the potassium loop. The increase in superheat at part load ensures that dry turbine inlet conditions can be maintained.

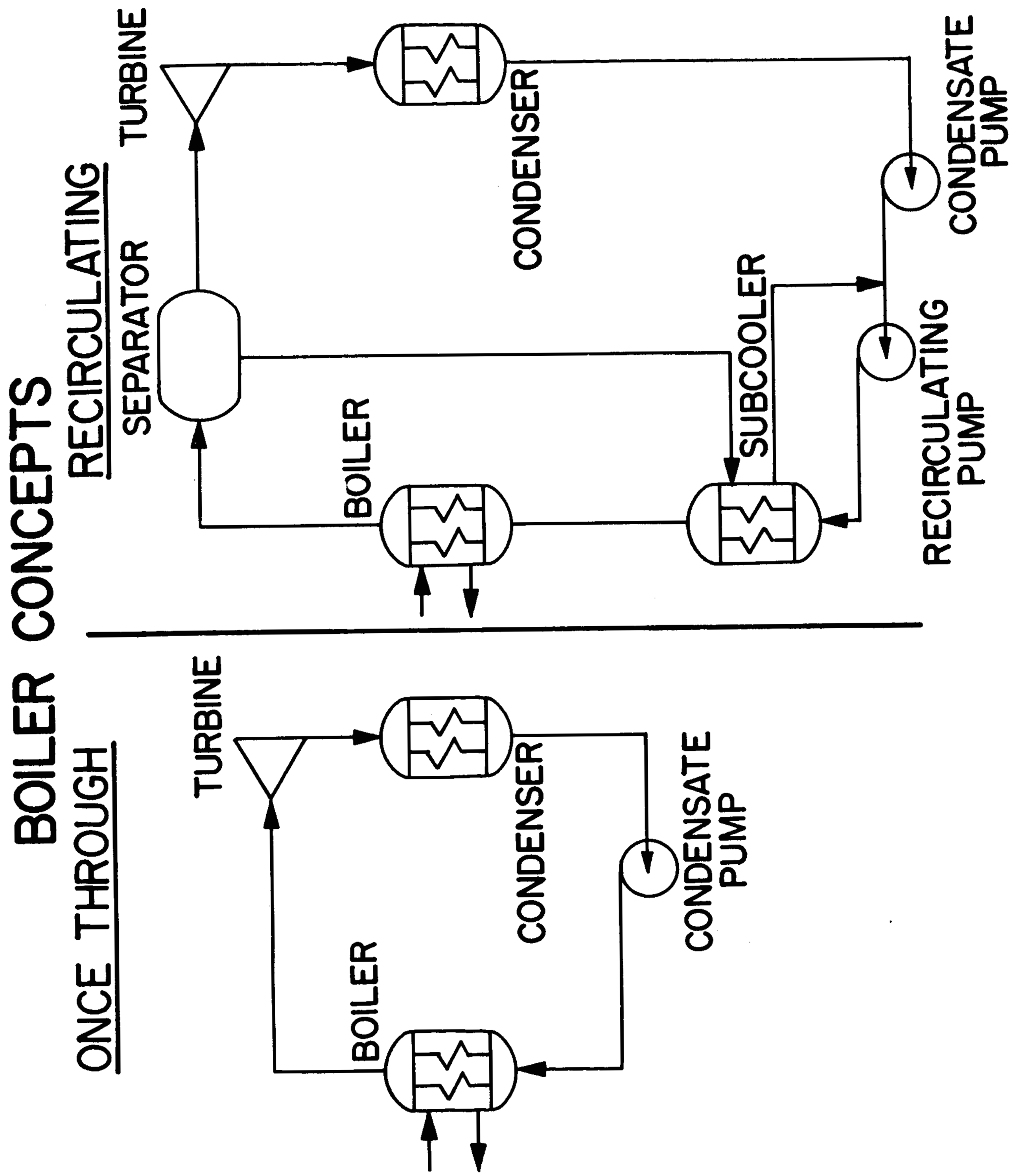
BOILER CONCEPTS
ONCE THROUGH
RECIRCULATING
TURBINE
CONDENSER
CONDENSATE PUMP
BOILER
TURBINE
SEPARATOR
CONDENSER
CONDENSATE PUMP
SUBCOOLER
RECIRCULATING PUMP
BOILER

Figure 7

Control of a recirculating boiler is generally accomplished by maintaining boiler fluid inventory between prescribed limits. This requires an integration of the difference between feed flow and vapor flow which can be conveniently provided if a stable interface exists so that a level signal can be generated. In the absence of a gravitational field such a signal will be difficult to generate. Separator design, part load performance, and recirculation control are additional problems which must be considered with the recirculating boiler system.

One concern with the once-through boiler is the possibility of dissolved impurities precipitating in the superheating region of the boiler. No direct experimental evidence has been uncovered dealing with an exactly analogous system; however, tests in progress at Brookhaven National Laboratories with sodium contained in Cb-1Zr alloy indicate that this may not be a problem. The Brookhaven tests include capsule tests and a single tube natural circulation boiling and superheating loop in which sodium is boiled at 2000°F and superheated to 2200°F. The performance of this loop has not changed in 4000 hours of operation and x-ray examination does not detect any buildup of deposits.

Study of Electrical System Characteristics

An optimization of the subsystem consisting of the turbine, generator, and power-conditioning equipment was performed. The weight variations of the combined turbine-generator were incorporated with the weight variations of the power-conditioning equipment and auxiliary pump motors to provide a minimum weight for the complete turbine and electrical subsystem. Weights and operating conditions were obtained for powerplants with a range of net electrical power outputs per power conversion loop from 250 to 1000 KWe.

Generator

Basic generator data developed by Westinghouse under NASA contract NAS5-1234 were modified to represent a total effective generator weight. . The tabulated generator weights given by Westinghouse were increased by 20 per cent to account for the rotor-shaft extensions, bearings, end bells, cooling tubes, and terminal boards. The electrical losses in the generator produce a penalty on the rest of the powerplant by requiring additional boiler and reacter power to compensate for these electrical losses. A system weight penalty of 10 lbs/KWe of electrical losses was imposed corresponding to a powerplant specific weight estimate of approximately 10 lbs/KWe. These electrical losses appear as heat which must be dissipated to space. A heat rejection system weight of 2.5 lbs/KW at 500°F, 1.0 lb/KW at 800°F, and 0.5 lb/KW at 1100°F was used to determine the total effective generator weight listed in Table 2.

Inspection of these total effective generator weight tabulations indicates high weights for an 1100°F average coolant temperature and significantly lower weights for the 500 and 800°F coolant temperatures, 500°F being, in general, slightly lower than 800°F. The generators with a 500°F coolant temperature were selected for further consideration since they represented a smaller advance in the current state of the art than the 800°F systems. The 500°F systems do require a greater radiator area for heat rejection than the 800°F systems. Although a 500°F coolant temperature has been selected, this temperature could be increased up to 800°F if generator development warrants, or if reduction in radiator area is desired.

In Figures 8, 9, and 10, total effective generator weight is plotted versus rpm for feasible generator designs of 300, 600 and 1000 KW with voltage and frequency as parameters. By inspection the 400 cps curves are seen to be considerably heavier than the 1000 and 2000 cps curves and were eliminated from further consideration.

Turbine

Parametric turbine data has been generated for multistage turbines with partial liquid extraction between stages and reported in Reference 2 without stress limits. Appendix 3 presents the turbine parametric data with stress limits. A turbine inlet condition of saturated potassium vapor at 1800°F was selected, based upon previous system studies. This turbine information was combined and plotted as Figure 11 which shows turbine weight versus rpm for various power levels and number of stages. All points on this curve represent turbines at the stress limit using an advanced columbium alloy. Reducing the stress is accomplished by moving to the left on the number of stages line for a given power output.

TABLE 2

Generator Parametric Data

Power	Frequency	Temp.	Voltage	Speed	Gen. Wt.	Gen. Losses	Weight for Losses	Rad. Wt.	Total Weight
KW	CPS	°F	Volts	rpm	lbs	KW	lbs	lbs	lbs
1000	400	500	1000	12000	3213	114.7	1147	287	4647
			1500		3483	129.2	1292	323	5098
			2140		3231	110.8	1008	277	4516
		800	1000		-	-	-	-	-
			1500		No Practical Design				
			2140		-	-	-	-	-
		1100	1000		-	-	-	-	-
			1500		-	-	-	-	-
			2140		-	-	-	-	-
	1000	500	1000	15000	1194	51.4	514	129	1837
			1500		1026	53.3	533	133	1692
			2140		1253	50.2	502	126	1881
		800	1000		1278	65.1	651	65	1994
			1500		-	-	-	-	-
			2140		-	-	-	-	-
		1100	1000		-	-	-	-	-
			1500		-	-	-	-	-
			2140		-	-	-	-	-
		500	1000	20000	1135	62.0	620	155	1910
			1500		1156	62.6	626	157	1939
			2140		972	56.1	561	140	1673
		800	1000		-	-	-	-	-
			1500		-	-	-	-	-
			2140		-	-	-	-	-
		1100	1000		-	-	-	-	-
			1500		-	-	-	-	-
			2140		-	-	-	-	-
	2000	1100	1000	4000	3910	130.3	1303	65	5278
			1500		4397	124.3	1243	62	5702
			2140		3706	124.4	1244	62	5012
		1100	1000	6000	1816	86	860	43	2719
			1500		1928	94	940	47	2915
			2140		2014	934	934	47	7995

TABLE 2 (Cont'd)

Power	Frequency	Temp.	Voltage	Speed	Gen. Wt.	Gen. Losses	Weight for Losses	Rad. Wt.	Total Weight
KW	CPS	°F	Volts	rpm	lbs	KW	lbs	lbs	lbs
1000	2000	500	1000	10000	982	66	660	165	1807
			1500		982	65.3	653	163	1789
			2140		1033	76	760	190	1983
		800	1000		984	65.7	657	66	1707
			1500		984	67.4	674	67	1725
			2140		1036	76.1	761	76	1873
		1100	1000		1187	82.3	823	41	2051
			1500		1277	137.4	1374	69	2720
			2140		1217	145.4	1454	73	2744
		500	1000	15000	677	56	560	140	1377
			1500		702	61.4	614	154	1470
			2140		726	74.0	740	185	1651
		800	1000		794	57.3	573	57	1424
			1500		806	58.8	588	59	1453
			2140		752	70.3	703	70	1525
		1100	1000		-	-	-	-	-
			1500		-	-	-	-	-
			2140		-	-	-	-	-
		500	1000	20000	582	52.3	523	131	1236
			1500		618	55.8	558	140	1316
			2140		641	64.7	647	162	1450
		800	1000		568	53.3	533	53	1154
			1500		674	59.4	594	59	1327
			2140		696	67.6	676	68	1440
		1100	1000		-	-	-	-	-
			1500		-	-	-	-	-
			2140		-	-	-	-	-
		500	1000	24000	550	53.3	553	138	1241
			1500		556	52.7	527	132	1215
			2140		605	57.3	573	143	1321
		800	1000		682	67.4	673	169	1525
			1500		672	66.6	666	167	1505
			2140		631	68.6	686	172	1489

TABLE 2 (Cont'd)

Power	Frequency	Temp.	Voltage	Speed	Gen. Wt.	Gen. Losses	Weight for Losses	Rad. Wt.	Total Weight
KW	CPS	°F	Volts	rpm	lbs	KW	lbs	lbs	lbs
1000	2000	1100	1000	24000	-	-	-	-	-
			1500		-	-	-	-	-
			2140		-	-	-	-	-
600	400	500	1000	8000	1648	38.2	382	96	2126
			1500		1339	35.5	355	89	1783
			2140		1483	34.0	340	85	1908
		800	1000		1657	47.3	473	47	2177
			1500		1346	44.0	440	44	1830
			2140		1489	40.7	407	41	1937
		1100	1000		-	-	-	-	-
			1500		-	-	-	-	-
			2140		-	-	-	-	-
		500	1000	12000	1824	58	580	145	2740
			1500		1723	51.3	513	129	2365
			2140		1374	50.9	509	127	2010
		800	1000		2235	60.5	605	61	2901
			1500		1909	58.7	587	59	2555
			2140		1658	61.2	612	61	2331
		1100	1000		-	-	-	-	-
			1500		-	-	-	-	-
			2140		-	-	-	-	-
	1000	500	1000	15000	581	32.2	322	81	984
			1500		592	34.8	348	87	1027
			2140		608	39.0	390	98	1096
		800	1000		618	38.7	387	39	1044
			1500		662	41.4	414	41	1117
			2140		708	47.0	470	47	1215
		500	1000	20000	606	36.3	363	91	1060
			1500		547	36.5	365	91	1003
			2140		610	37.6	376	94	1089
		800	1000		700	49.8	498	50	1248
			1500		622	45.7	457	46	1175
			2140		680	45.3	453	45	1178

TABLE 2 (Cont'd)

Power	Frequency	Temp.	Voltage	Speed	Gen. Wt.	Gen. Losses	Weight for Losses	Rad. Wt.	Total Weight
KW	CPS	°F	Volts	rpm	lbs	KW	lbs	lbs	lbs
600	1000	500	1000	30000	718	53.4	534	134	1386
			1500		714	52.6	526	132	1372
			2140		542	48.2	482	118	1142
		800	1000		629	62.5	625	63	1317
			1500		710	67.4	674	67	1451
			2140		667	69.7	697	70	1434
	2000	500	1000	15000	492	44.1	441	110	1043
			1500		524	40.1	401	100	1025
			2140		512	42.7	427	107	1046
		800	1000		532	47.1	471	47	1050
			1500		559	48.3	483	48	1090
			2140		545	44.0	440	44	1029
		500	1000	20000	410	39.6	396	99	905
			1500		428	39.9	399	100	927
			2140		-	-	-	-	-
		800	1000		446	44.0	440	44	930
			1500		486	49.1	491	49	1026
			2140		455	43.5	435	44	934
		500	1000	30000	355	37.9	379	95	829
			1500		359	41.0	410	103	872
			2140		360	40.4	404	101	865
		800	1000		394	46.5	465	47	906
			1500		404	49.6	496	50	950
			2140		397	49.8	498	50	945
300	400	500	1000	8000	666	22.3	223	56	945
			1500		565	24.1	241	60	979
			2140		738	23.0	230	58	1025
		800	1000		671	28.5	285	29	984
			1500		682	30.9	309	31	1021
			2140		742	28.9	289	29	1059

TABLE 2 (Cont'd)

Power	Frequency	Temp.	Voltage	Speed	Gen. Wt.	Gen. Losses	Weight for Losses	Rad. Wt.	Total Weight
KW	CPS	°F	Volts	rpm	lbs	KW	lbs	lbs	lbs
300	400	500	1000	12000	512	24.7	247	62	924
			1500		696	25.8	258	65	1018
			2140		667	30.7	307	77	1051
		800	1000		748	35.6	356	36	1140
			1500		1061	43.5	435	44	1539
			2140		822	43.9	439	44	1305
		500	1000	24000	902	80.7	807	202	1912
			1500		854	84.9	849	212	1916
			2140		1072	70.0	700	175	1947
		800	1000		-	-	-	-	-
			1500		-	-	-	-	-
			2140		-	-	-	-	-
	1000	500	1000	15000	336	23.7	237	60	632
			1500		352	24.5	245	61	659
			2140		364	29.0	290	73	726
		800	1000		372	28.4	284	28	684
			1500		383	31.4	314	31	729
			2140		406	36.1	316	32	803
		500	1000	20000	314	22.8	228	57	599
			1500		317	25.4	254	64	634
			2140		344	27.6	276	69	690
		800	1000		343	29.1	291	29	663
			1500		354	32.0	320	32	706
			2140		376	32.7	327	33	735
		500	1000	30000	278	26.4	264	66	608
			1500		293	27.0	270	68	630
			2140		307	30.8	308	77	692
		800	1000		331	33.7	337	34	701
			1500		338	36.1	361	36	736
			2140		337	43.2	432	43	813
	2000	500	1000	15000	283	29.8	298	75	656
			1500		284	27.9	279	70	633
			2140		314	34.9	349	87	751

TABLE 2 (Cont'd)

Power	Frequency	Temp.	Voltage	Speed	Gen. Wt.	Gen. Losses	Weight for Losses	Rad. Wt.	Total Weight
KW	CPS	°F	Volts	rpm	lbs	KW	lbs	lbs	lbs
300	2000	800	1000	15000	300	27.7	277	28	605
			1500		294	32.9	329	33	656
			2140		329	37.7	377	38	744
		500	1000	20000	230	24.1	241	60	532
			1500		242	25.7	257	64	564
			2140		-	-	-	-	-
		800	1000		259	28.8	288	29	576
			1500		248	31.9	319	32	599
			2140		295	35.2	352	35	683
		500	1000	30000	204	24.8	248	62	514
			1500		204	30.1	301	75	581
			2140		230	30.5	305	76	612
		800	1000		229	30.4	304	30	563
			1500		224	30.5	305	31	560
			2140		246	40.3	403	40	689

GENERATOR TOTAL EFFECTIVE WEIGHT

POWER 300KW COOLANT TEMPERATURE 500°F

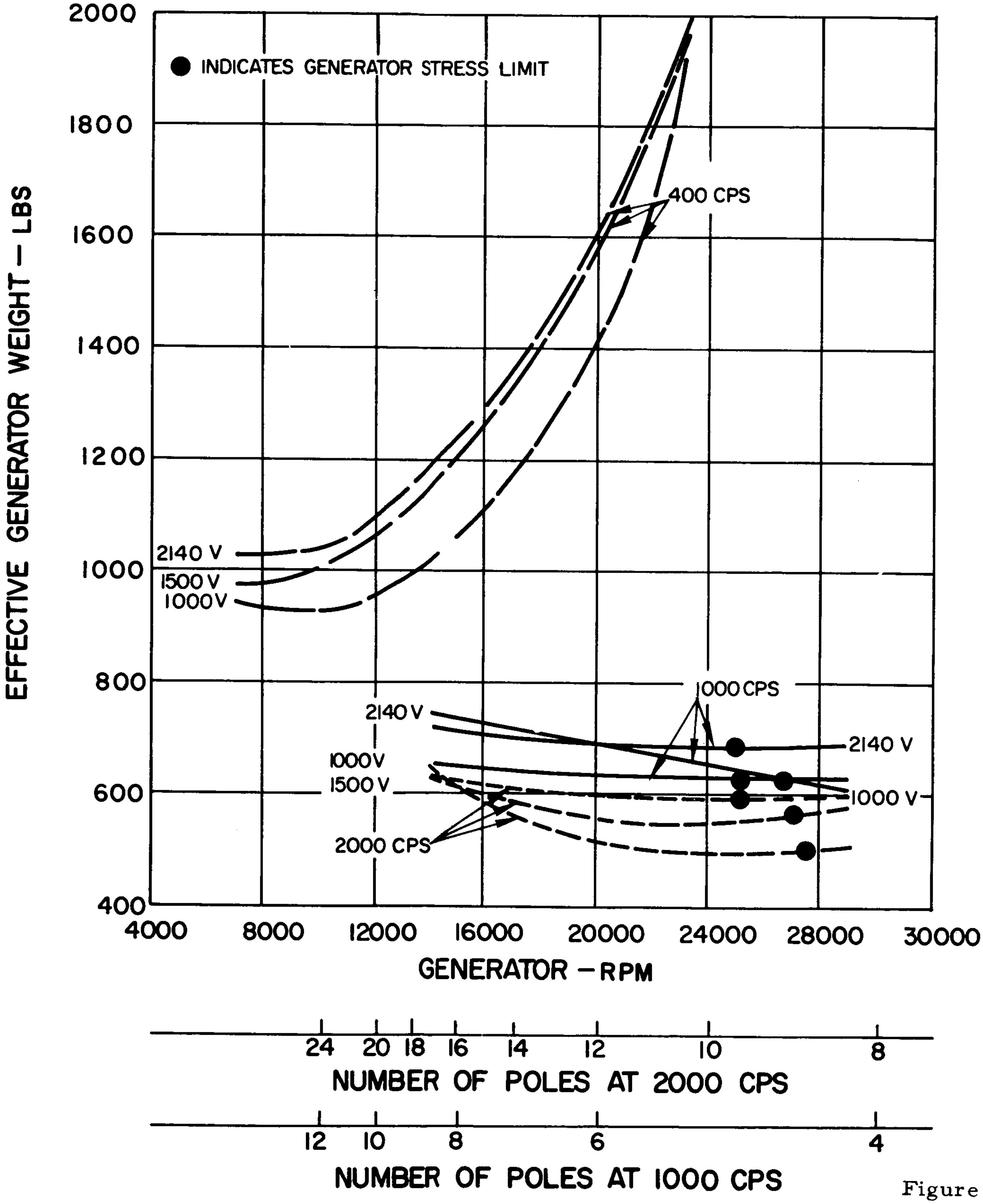

Figure 8

GENERATOR TOTAL EFFECTIVE WEIGHT

POWER 600KW

COOLANT TEMPERATURE 500°F

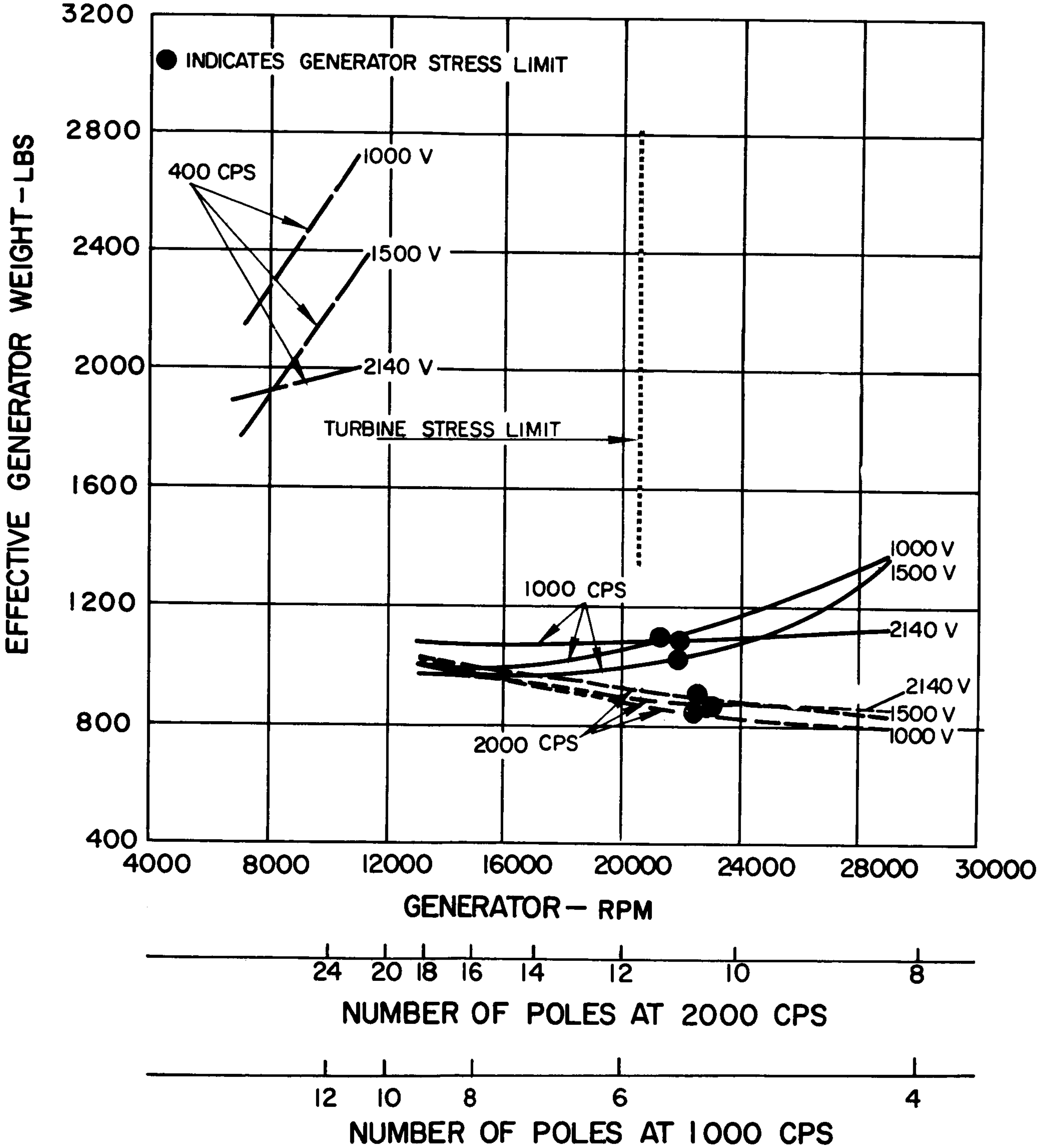

Figure 9

GENERATOR TOTAL EFFECTIVE WEIGHT

POWER 1000KW   COOLANT TEMPERATURE 500°F

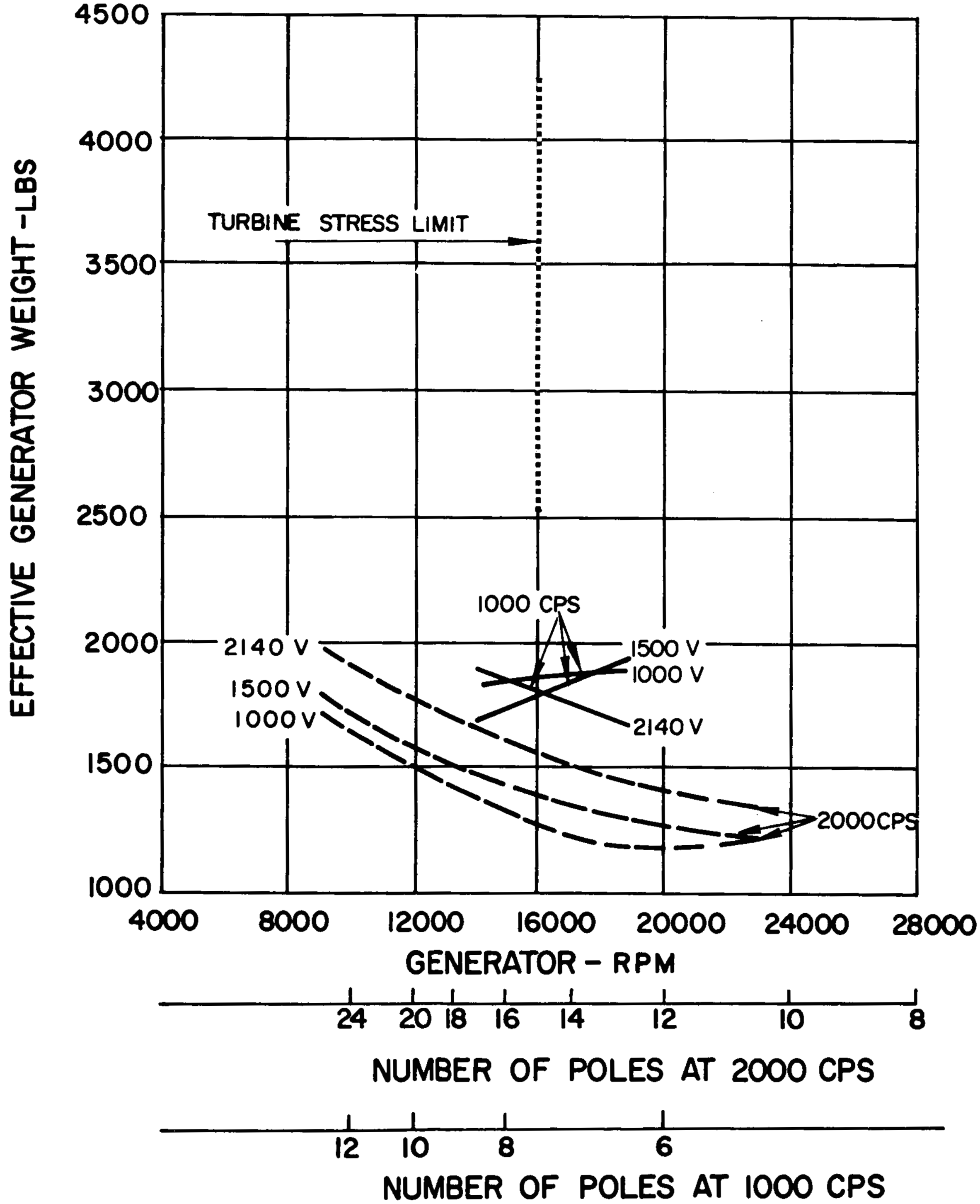

Figure 10

[redacted] CHARACTERISTICS
TURBINE INLET TEMPERATURE 1800°F
BLADE STRESS LIMITS
BASED ON AN ADVANCED COLUMBIUM ALLOY

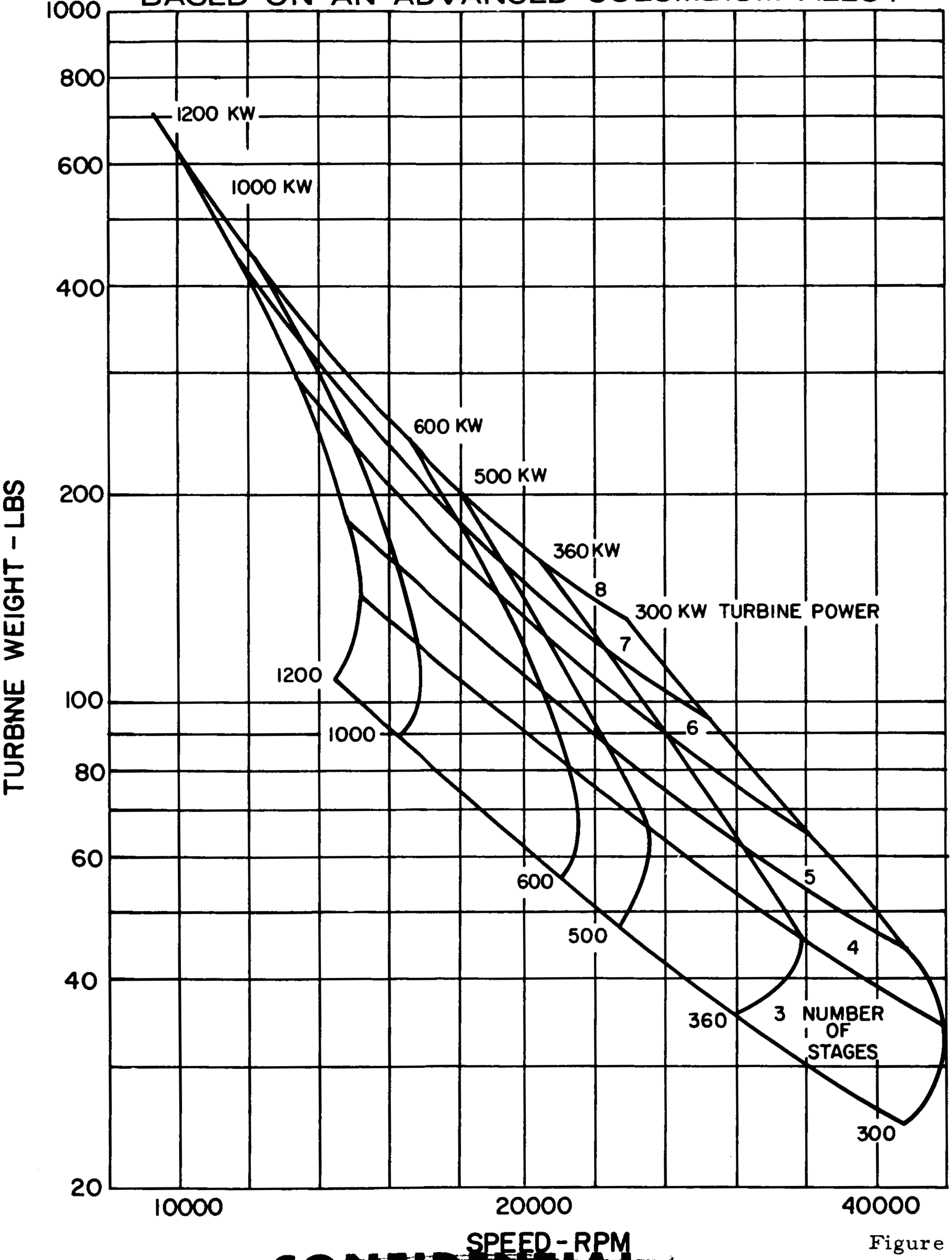

Figure 11

[redacted]

Combined Turbine-Generator Unit

The turbine and generator data were combined to match the speeds without exceeding the stress limit of either. In addition, the numbers of poles in the generator for the two frequencies, 1000 and 2000 cps, impose discrete values of rpm. The results of matching the generator and turbine are summarized in Table 3 and Figure 12. The assumption was made that turbine shaft power and generator output power were identical in this matching. Since the generator efficiency is in the order of 95 per cent this assumption does not appear to introduce significant error. As shown in Figures 8, 9, 10 and 11, the turbine blade stress limits rpm before generator rotor stress is reached for the 500°F generator coolant temperature.

Power-Conditioning Equipment

Parametric data were obtained for the power-conditioning equipment from References 1, 3 and 4. Data for the one megawatt power-conditioning system were used to evaluate the effects that would influence the generator selection. Results of the one megawatt power conversion system analysis will be typical of those for other power levels.

The exciter-regulator is based upon a three-phase full-wave silicon-controlled rectifier circuit cooled with an organic coolant. The transformer weight is relatively insensitive to voltage in the range of interest, however, it does increase with decreasing frequency. The silicon diode rectifier unit using cold plate cooling at 170°F was selected. The weight of this unit is insensitive to frequency over the range of interest and output voltage. Bank switches have been included to provide added flexibility which could permit either rectifier input or output variations depending upon the specific design.

The integration of the turbine generator unit with the power conversion equipment is shown in Table 4. In general the weight of the power-conditioning equipment is relatively insensitive to voltage and frequency over the range of interest.

TABLE 3

Combined Turbine and Generator Characteristics

Generator conditions	1000 CPS-1000 V (L-N)			1000 CPS-2140 V (L-N)			2000 CPS-1000 V (L-N)			2000 CPS-2140 V (L-N)		
Net electrical power, KW	1000	600	300	1000	600	300	1000	600	300	1000	600	300
Speed, rpm	15000	15000	20000	15000	15000	20000	13300	17150	24000	13300	17150	24000
Number of poles	8	8	6	8	8	6	18	14	10	18	14	10
Actual generator weight, lbs	1194	581	314	1253	608	344	735	590	210	785	615	260
Effective generator weight, lbs	1837	1000	600	1881	1025	690	1460	970	510	1725	995	665
6-Stage turbine weight	235	235	135	235	235	135	310	180	95	310	180	95
Turbine-generator actual weight	1429	816	449	1488	843	479	1045	770	305	1095	795	355
Turbine-generator effective weight, lbs	2072	1235	735	2116	1260	825	1770	1150	605	2035	1175	760

TURBINE & GENERATOR EFFECTIVE WEIGHT
vs.
GENERATOR POWER OUTPUT

6-STAGE TURBINE   500°F COOLANT TEMPERATURE

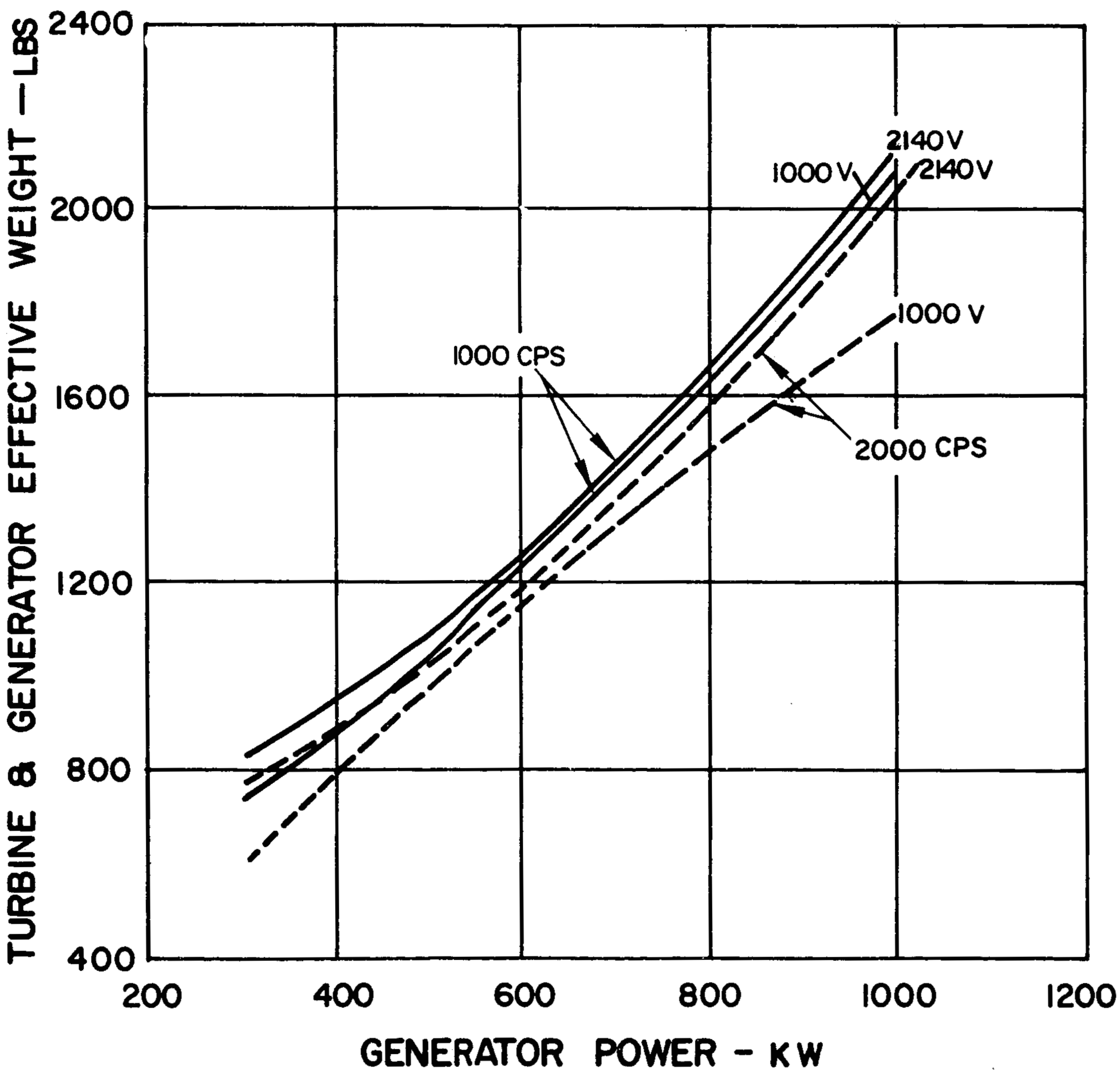

Figure 12

TABLE 4

Total Effective Weights - 1 MW Turbine-Generator and Power-Conditioning Equipment

Component	1000 V 1000 cps	1000 V 2000 cps	2140 V 1000 cps	2140 V 2000 cps
Exciter regulator, lbs	26.5	25.5	26.5	25.5
Circuit breakers, lbs	22.5	22.5	10.0	10.0
Transformer, lbs	531	487	531	487
Rectifiers, lbs	355	355	355	355
Bank switch, lbs	300	300	300	300
Subtotal, lbs	1235	1190	1223	1178
Turbine-generator, lbs	2072	1770	2116	2035
Total, lbs	3307	2960	3330	3213

Pump Motors

Based upon previous cycle studies two primary pump motors are required with a power input of approximately 30 KWe and 16 radiator pump motors with a power input of approximately 1 KWe each are required for a 1 MWe powerplant. The electric motor parametric data were modified to reflect a total effective weight. This consisted of adding 20 per cent to the basic electrical weight, adding 2.5 lbs/KWe loss to account for heat rejection radiators, and adding 10 lbs/KWe loss to account for the weight increase of the rest of the system to compensate for electrical losses. The total effective motor weights for the two primary pump motors and the 16 radiator pump motors are shown in Table 5. A speed of 10,000 rpm was selected for all the motors since this gives acceptable values of both suction specific and specific speed for the pumps.

Combining the effective weights of the turbine, generator, and power-conditioning equipment with the motor effective weights gives the following results.

Condition	Total Effective Weight
1000V, 1000 cps	3948 pounds
1000V, 2000 cps	3788
2140V, 1000 cps	4047
2140V, 2000 cps	4141

Based upon the above results, 1000 V systems are seen to be lighter than the 2140 V systems. A 1000 V system has been selected on this basis. Although the 1000 cps is approximately 160 pounds heavier than the 2000 cps system, it was selected. This was done primarily to ease the motor design problems by reducing the number of poles required and also to operate nearer the conventional range of frequencies.

Turbine-Generator and Power-Conditioning Equipment Characteristics and Actual Weights

The weight and characteristics of the turbine-generator and power-conditioning equipment have been tabulated in Table 6 for net power outputs of 1000, 500, 300 and 250 KWe. For these systems the generated power was obtained by increasing the net power by 20

[redacted]

TABLE 5

Total Effective Weight - Radiator and Primary Pump Motors

Frequency, cps	Voltage, Volts	Primary Pump Motor Weight, lbs	Radiator Pump Motor Weight, lbs	Total Weight, lbs
2000	2140	640	288	928
	1000	580	248	828
	120	550	200	750
800	2140	500	208	708
	1000	460	181	641
	120	440	152	592
400	2140	460	176	636
	1000	440	160	600
	120	400	136	536

Basis: 16 radiator pumps at 1 KWe each (input power)
2 primary pumps at 30 KWe each (to motors)
10,000 rpm motor

TABLE 6

Component Weights and Radiator Weights: Fm Turbine to Rectifiers

Net electrical output, KW	1000	500	300	250
Generator output, KW	1200	600	360	300
Turbine Wt, lbs.	300	160	95	95
Generator				
Weight, lbs.	1620	581	350	314
Speed, rpm	12000	15000	20000	20000
Poles	10	8	6	6
Losses, KW	45	32	26	24
Rad Wt, lb	113	80	65	60
Total weight of power-conditioning system	957	479	287	239
Total weight, lbs.	2990	1300	797	708
Specific weight, lbs/KWe	2.99	2.60	2.66	2.83

Weight of Power-Conditioning System at 1000 KW Net

Power-conditioning equipment	WT lbs.	Losses KW	Temp. °F	Wt. Rad lbs.	Total Wt. lbs.
Exciter regulator	16	0.3	122	8	
Circuit breaker	12	0.4	500	5	
Transformer	350	13.5	1000	11	
Rectifiers	163	7.2	171	127	
Bank switch	240	1.0	400	25	
Total	781			176	957

Basis: 500°F, 1000 cps, 1000 V, 6-stage turbine per cent to account for losses and powerplant electrical requirements such as pump motors. Power-conditioning equipment weights are based upon net power output and both weight and losses are scaled linearly from the 1000 KWe system for lower powers.

APPENDIX 1

References

APPENDIX I
References

1. Extended 1-10 Megawatt Study Contract NAS5-1234; Parametric Data for 250KW to 500KW Electric Power System; Westinghouse Electric Corporation Aerospace Electrical Division, Lima, Ohio

2. Quarterly Progress Report, Advanced Nuclear-Electric Power Generation System Study. Report PWA-2107 Volume III Rankine Cycle Nuclear Space Powerplant. Pratt & Whitney Aircraft Division, East Hartford, Connecticut

3. Space Electric Power Systems Study, Progress Report - Third Quarter, Contract NAS5-1234

4. Space Electric Power Systems Study, Progress Report - Second Quarter, Contract NAS5-1234

5. ARS Report, Alkaline Metal Two-Phase Heat Transfer for Space Power, R. D. Break and S. G. Sawochka, General Electric Company, September 1962

APPENDIX 2

Turbine Analysis

APPENDIX 2
Turbine Analysis

The limits which blade stress impose on turbine design are shown for inlet temperatures of 1600, 1800 and 2000°F in Figures 13, 14, and 15 respectively. These curves show the inlet flow required as a function of turbine shaft power with the number of turbine stages as a parameter. The maximum power that can be generated without exceeding blade stress limits is shown for an advanced columbium alloy. This alloy has significantly better high temperature strength than Cb-1Zr and has good room temperature fabrication properties. The stress limits were calculated at 10,000, 20,000, and 30,000 rpm. Figure 16 shows the design properties of the alloy which were used to determine the turbine stress limits. The information is based on extrapolation of of test data for 400 to 500 hours at or near the indicated temperatures.

VAPOR FLOW RATE
vs.
POWER WITH BLADE STRESS LIMITS
COLUMBIUM BASE ALLOY

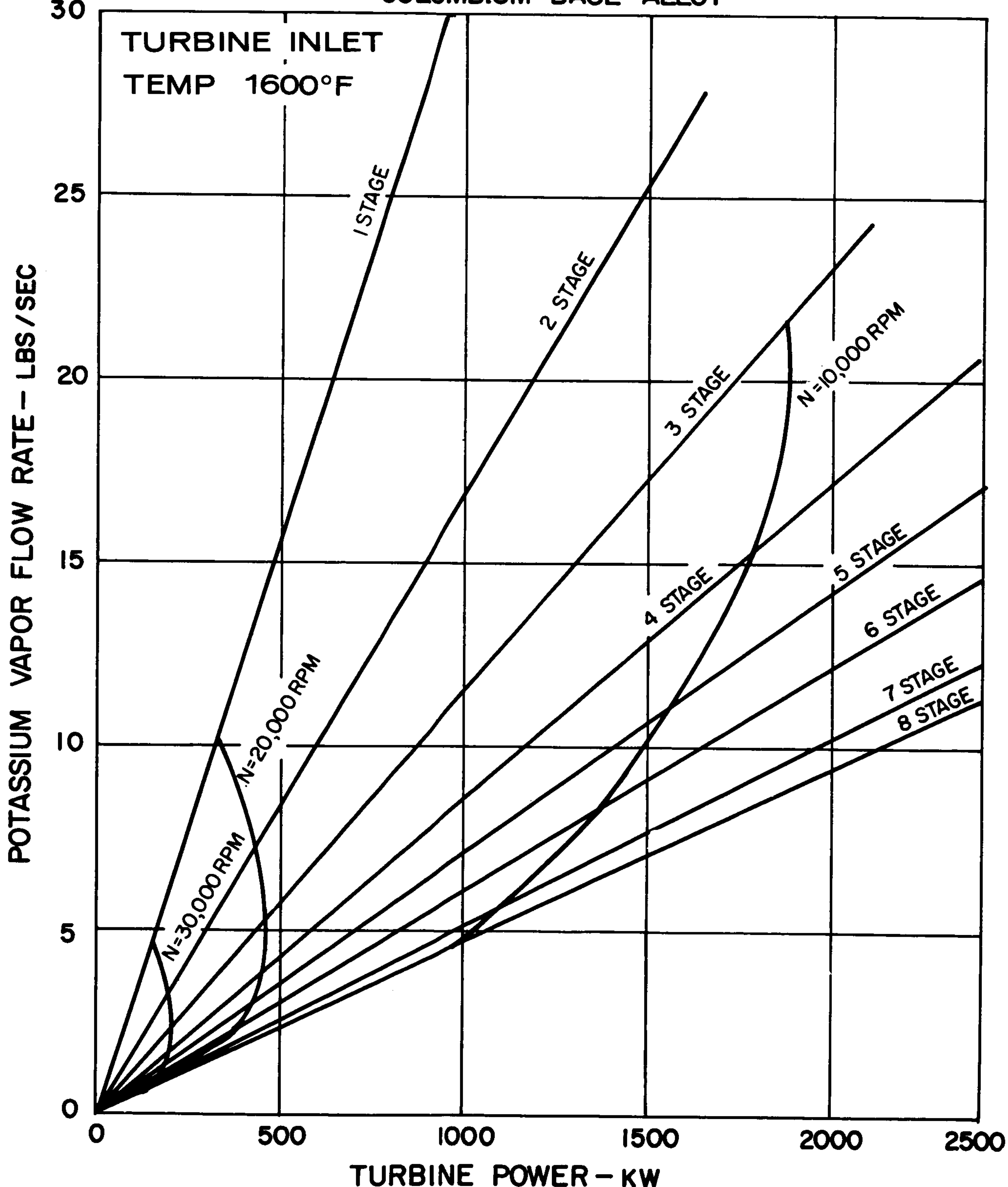

Figure 13

VAPOR FLOW RATE
VS.
POWER WITH BLADE STRESS LIMITS

COLUMBIUM BASE ALLOY

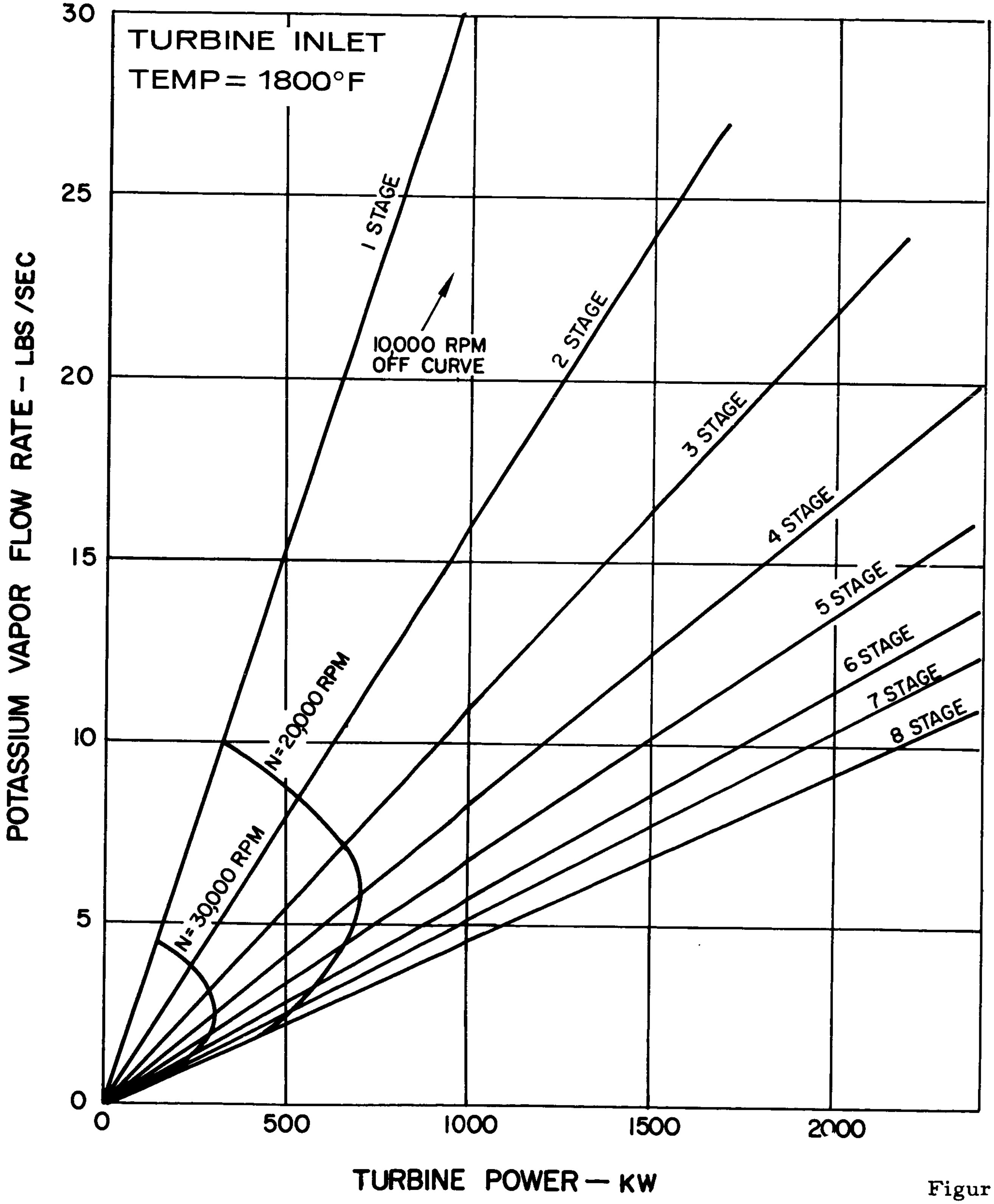

Figure 14

VAPOR FLOW RATE
vs.
POWER WITH BLADE STRESS LIMITS

COLUMBIUM BASE ALLOY

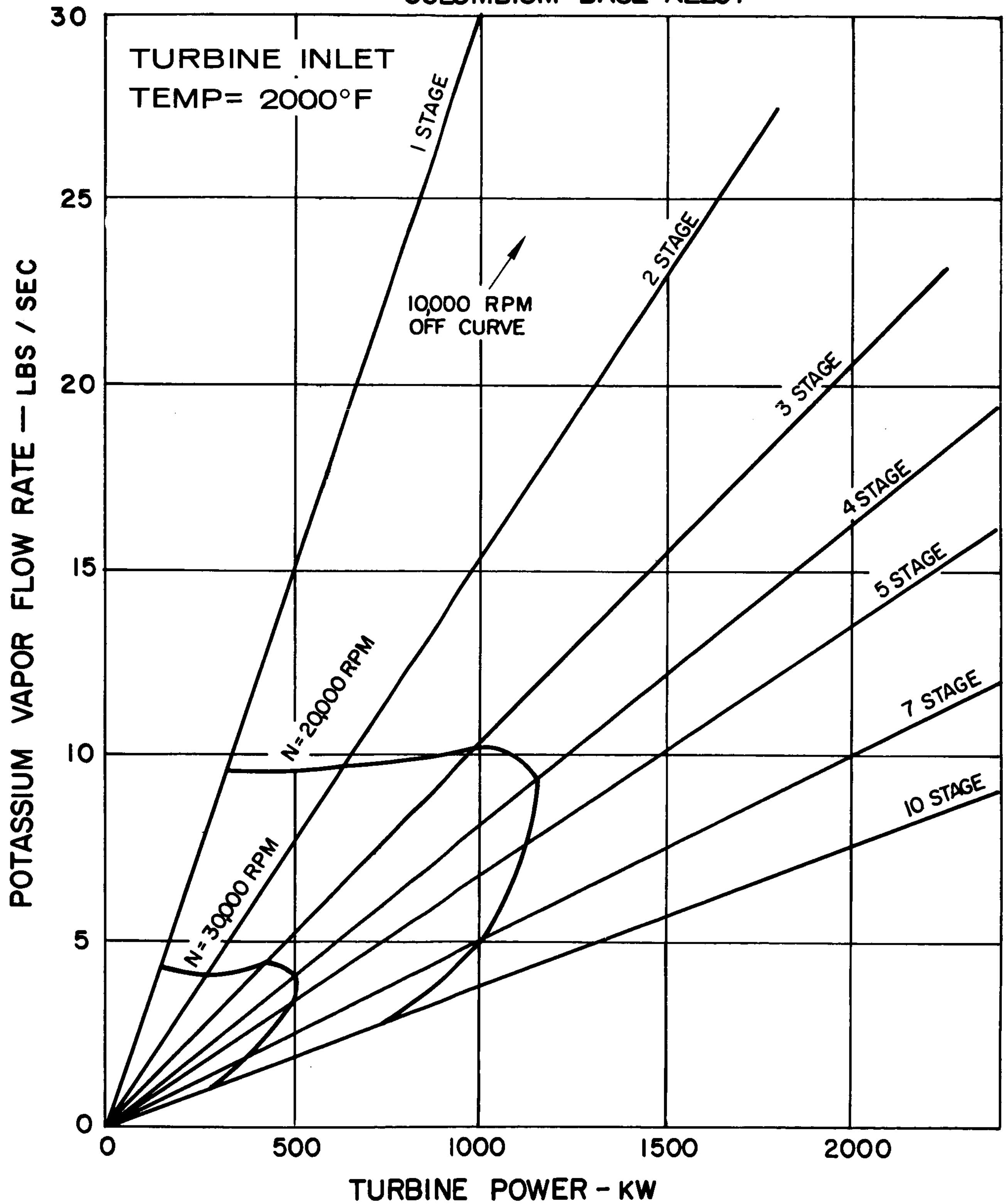

Figure 15

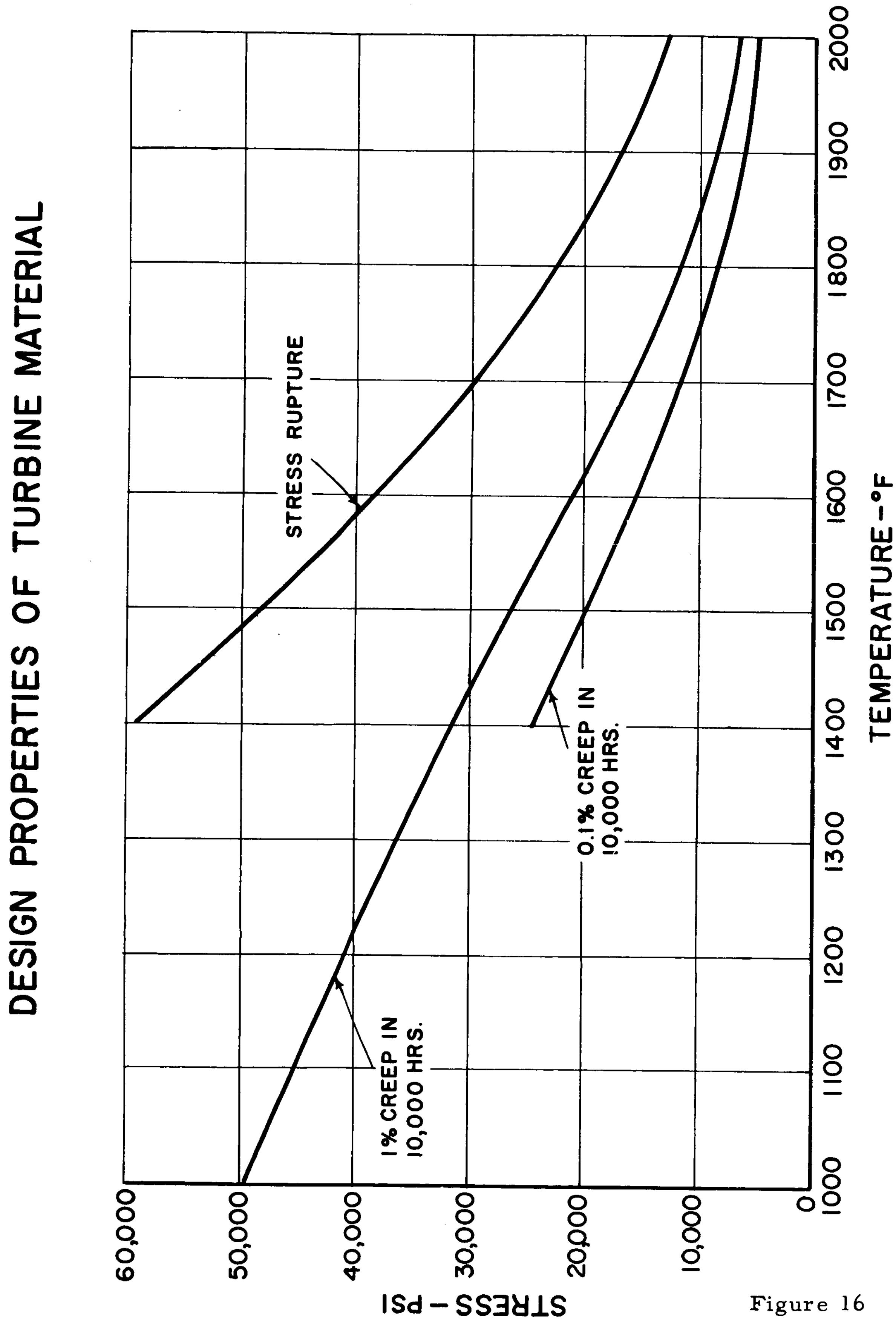
DESIGN PROPERTIES OF TURBINE MATERIAL
STRESS RUPTURE
1% CREEP IN 10,000 HRS.
0.1% CREEP IN 10,000 HRS.
TEMPERATURE -°F
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
STRESS - PSI
0
10,000
20,000
30,000
40,000
50,000
60,000

Figure 16